PHYSICAL AND MATHEMATICAL MODELING OF WAVE PROPAGATION IN THE ARIANE 5 VEB STRUCTURE

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Abstract—The separation of the lower stage of the ARIANE 5 Vehicle Equipment Bay (VEB) Structure is to be done using a pyrotechnic device. The wave propagation effects produced by the explosion can affect the electronic equipment, so it was decided to analyze, using both physical and numerical modeling, a small piece of the structure to determine the distribution of the accelerations and the relative importance of damping, stiffness, connections, etc. on the response of the equipment.

1. INTRODUCTION

This paper describes the numerical and experimental study performed by CASA Space Division, the Structural Mechanics Department of the Polytechnical University of Madrid (UPM) and the Society SIN X, under the ARIANE 5 Vehicle Equipment Bay (VEB) Structure Preparatory Program, related to the shock induced in the VEB structure.

The separation of the lower stage of the ARIANE 5 VEB is produced by a pyrotechnic device that produces the sudden rupture of the connecting ring. In order to analyze the accelerations induced in different parts of the structure, a preliminary program including both experimental and analytical studies was launched. A first report of the results obtained when treating a model simulating the general scheme of the cross-section of the structure was described in Ref. 1. It was then decided to study the influence of the inclusion of concentrated damping at selected knots by using layers of a special plaster intercalated among the different connection parts, and to compare the results of using that alternative to smooth the acceleration peaks on the equipment plate. The comparison was also intended to test the accuracy of different computational methods, to help in the assignment of the material properties and to detect local efforts not easily previewed without an experimental substantiation. A multidisciplinary team including mechanical, aeronautical and civil engineers was organized in order to cover the laboratory as well as the theoretical aspect of the analysis. The results obtained have disclosed several interesting and unexpected phenomena and also the capability of the numerical methods to model, within a reasonable accuracy range, the problem. It is expected that the methods used can be extended to the more complicated situation of the actual problem.

2. EXPERIMENTAL WORK

Experiments have been conducted on a small strip of a cross-section of the real structure. Figure 1 shows a close-up of the specimen in which a large mass is resting on the equipment plate (honeycomb + aluminium skins) which, in turn, is supported by a couple of aluminium members transmitting the load to the composite (CFRP sandwich) cone, a strip of which has also been cut from the large specimen. The load is applied to an aluminium piece of ring (lower left of the picture) that is the result of the pyrotechnic cutting.

The whole specimen was hung from a rigid gable through elastic connections and different types of loads were applied to the ring, including the explosion of small pyrotechnic "petards" and shocks induced by hammers with instrumented heads.

Several modal analyses were also performed to assess the boundary conditions and the material properties at low frequencies. The data were obtained using eight accelerometers distributed in locations selected to aid the back interpretation. All data were analyzed and stored in a computerized system consisting of an AMPEX signal recorder with a band pass of 40 kHz and an SD 380 signal analyzer controlled by an HP 9000-320 computer.

To aid in understanding the situation, model A of Fig. 2 presents a scheme of the discretized model used to conduct the numerical experimentation.

3. NUMERICAL MODEL AND COMPUTATIONAL METHOD

The modeling of the structure has been done using bar elements with the capability of including axial, flexural and shear deformation as well as the influence of the rotational inertia, which can be very important in treating the finite size of the large rigid

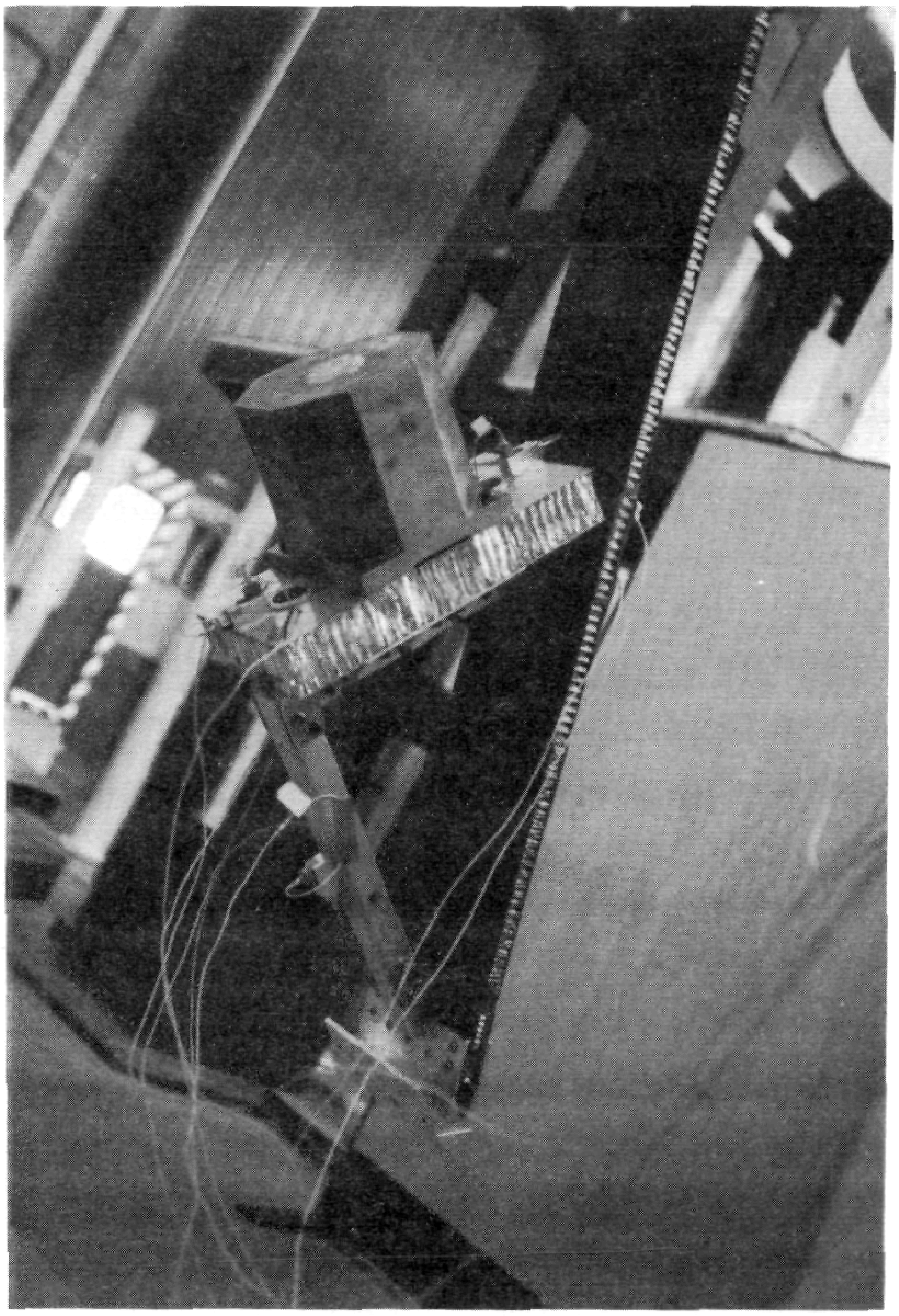

Fig. 1. Test sample.

mass. The beams are of the so called Timoshenko–Rayleigh type, as explained below, in order to be able to use elements as large as is permitted by the geometrical or material properties of the structure.

Additionally, a series of concentrated spring–dashpot systems has been included by duplicating selected nodes (mainly in the nodes of the equipment plate supporting structure) to take into account the influence of local node stiffnesses, areas of concentrated damping and local masses.

The study has been developed in three steps. An initial model was built up following the experience gained in previous studies and the adjustments to the modal test performed in the past. The results of a parametric study suggested certain modifications to the equipment plate. Finally, in order to reproduce the horizontal acceleration registered on that plate, a third model in which the rigid mass is detached from the plate, was developed (models B and C of Fig. 2).

As can be seen in the first model (model A) the plate was modeled as a single beam with the concentrated mass incorporated in the central third of the beam, including both the translational and the rotational inertia. The second model (model B) family was an effort to improve the plate modeling by translating the reference line to the upper skin and concentrating the mass in the upper end of the central insert, where stiffness is much larger than that in the plate core. Finally, it was considered that the attachment of the mass to the plate through poting binding could not be thought of as rigid, and a final model (model C) was built in which an elastic attachment was introduced between mass and plate.

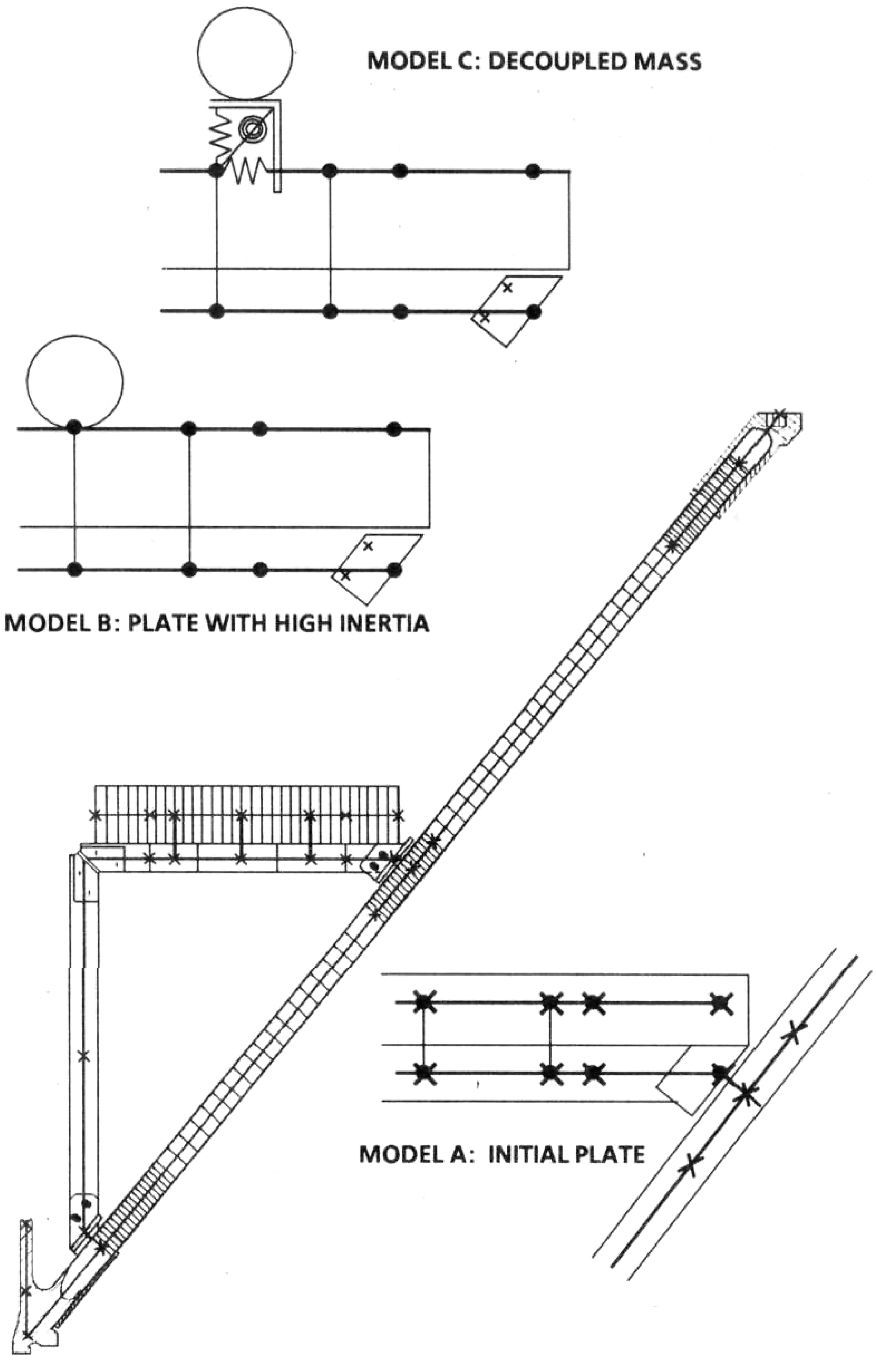

Fig. 2. Mathematical models.

In each family a difference was introduced in order to distinguish between undamped and damped specimens; the main differences are related to the description of the connecting nodes and the plate attachments to the structures.

To obtain the presented results a computer program has been developed which takes special account of the properties of the problem at hand.

The most important feature is the analysis in the frequency domain due to the possible need to include a frequency dependent damping and the need to reflect the dissipative nature of the flexural waves.

Consequently, it is neccessary to have available a computational system allowing the computation of the structural response for every harmonic component of the excitation as well as a subsequent superposition procedure to compose the response in the time domain.

Until now,[1] that process has been organized using a program called ONDA-F, able to analyze frames composed of Euler–Bernoulli beams, by a process which keeps track of the wave propagation until the stady-state situation is reached. That computation is reported for every frequency.

The procedure, unbeatable when used to follow the evolution of non-dispersive waves (i.e. applied directly to the time domain), presents in our case two main inconveniences: the computer time grows with the number of frequencies used in the Fourier transform and with the number of load cases to be analyzed. That is, the cost of parametric studies is heavily penalized by computer time.

The course of action taken has been the organization of a new computer program using as shape functions the analytical solution to the frequency response of a Timoshenko–Rayleigh beam; in that

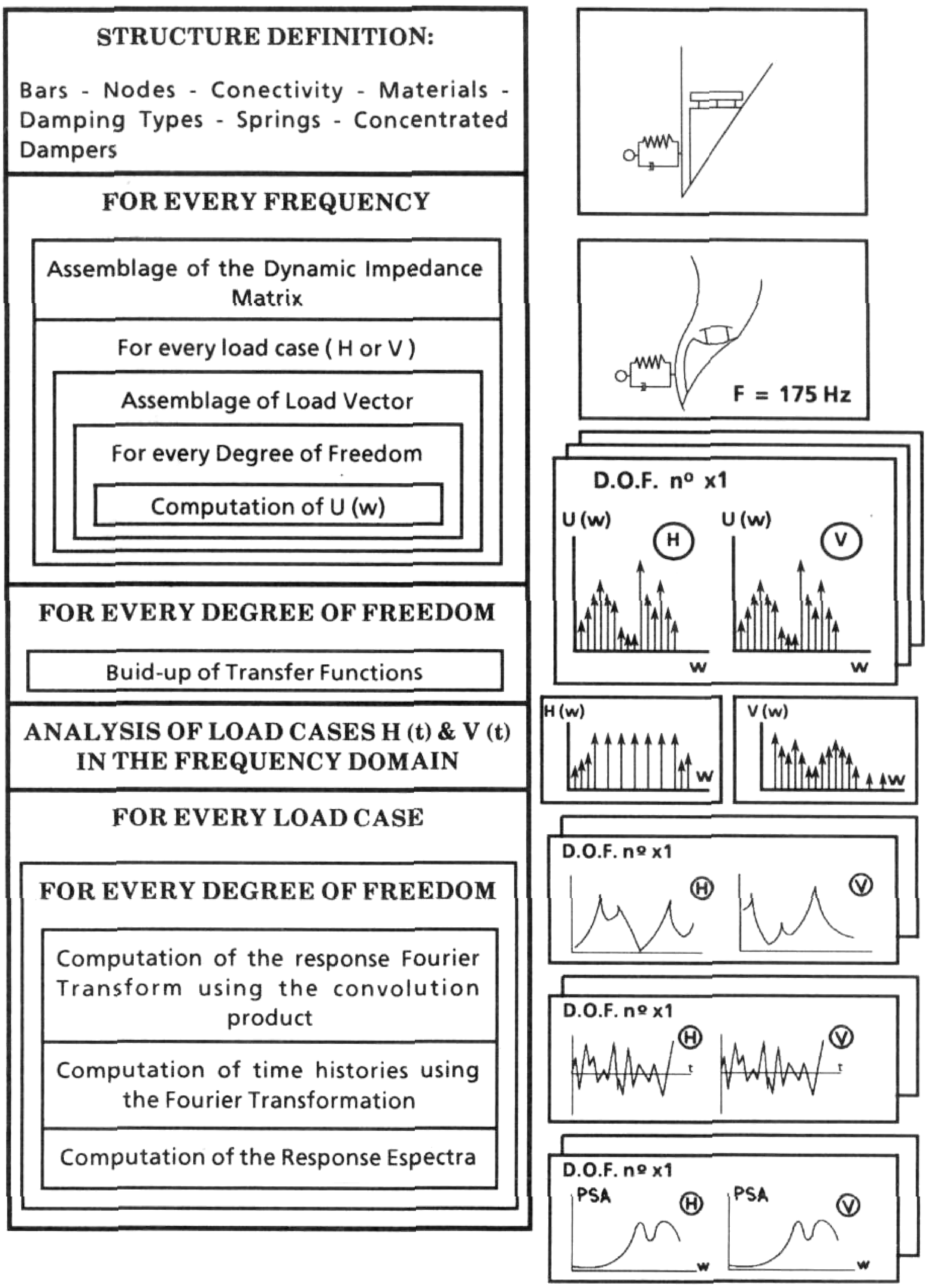

Fig. 3. Mathematical method scheme.

way the discretization can have elements as large as possible, depending on the material properties and boundary conditions. Moreover, an enormous number of possibilities in the treatment of concentrated masses, springs and dashpots, either with respect to a fixed frame of reference or between nodes, is open for translational as well as rotational degrees of freedom.

Working in the frequency domain, it is very simple to introduce the concept of a complex stiffness incorporating the effects of the distributed and/or concentrated masses, as well as elastic or dissipative elements. If, in the frequency domain, the field equation is solvable, the computation of the impedance matrix is immediate by application of the correct unit boundary displacement. As indicated above, a Timoshenko–Rayleigh model has been used; that model includes the effects of shear deformation as well as those of rotatory inertia of the cross-section, and allows, by using complex elasticity E and shear G moduli, the consideration of different damping types: viscous, hysteretic and variable with frequency following a desired law.

The most interesting advantages of this method are as follows.

(a) Intrinsic speed of computation due to the simultaneous study, for every frequency, of various load cases without substantial time increase.

(b) Faster speed by reducing the number of degrees of freedom; in the ONDA-F method it is necessary to establish control nodes at distances

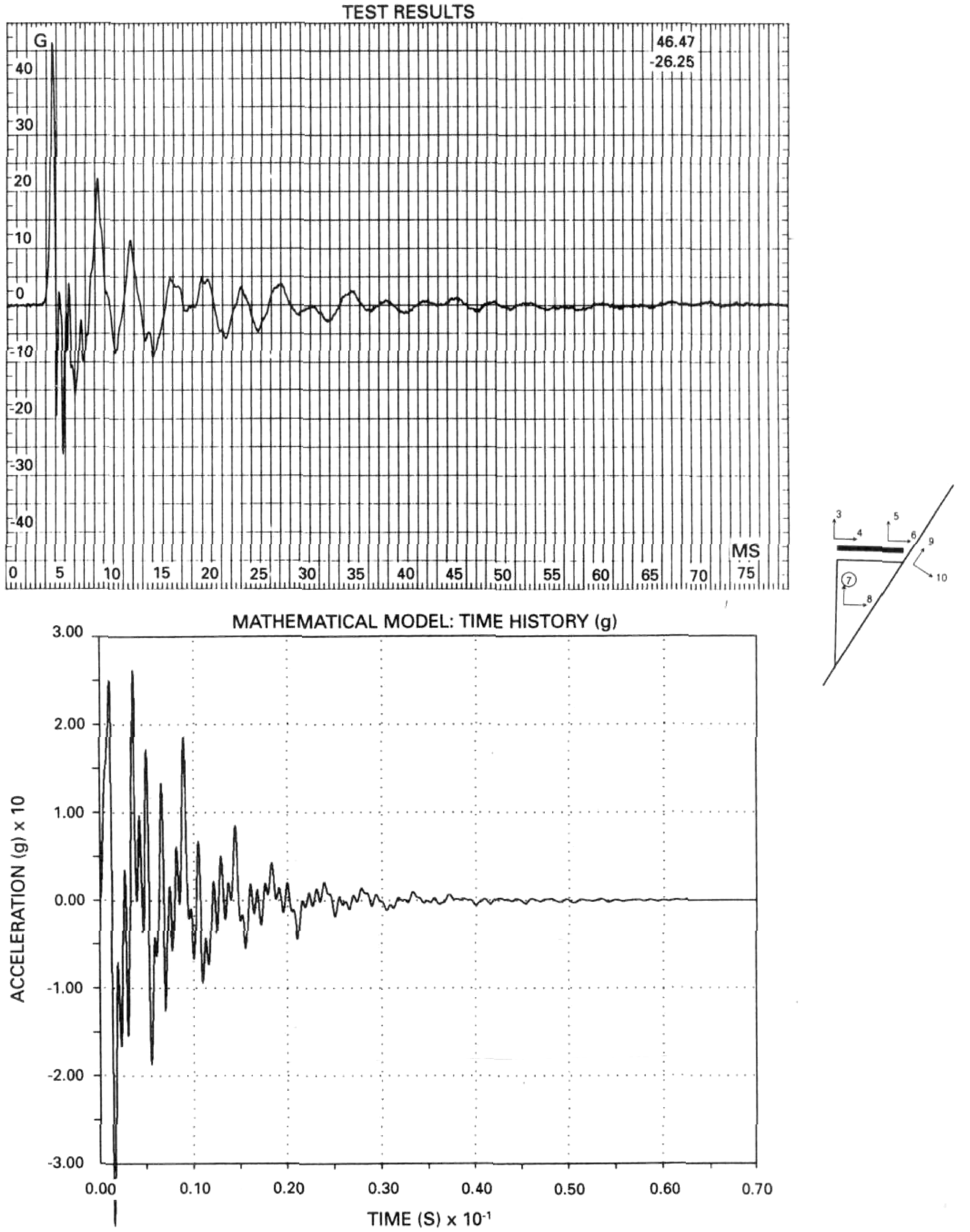

Fig. 4. Test and theoretical results.

that have to be consistent with the propagation parameters, which increase the demand of control nodes and required storage. With the proposed method, the number of elements is the minimum compatible with the variation of geometrical and material properties.

(c) The possibility of computing the response at internal nodes because the interpolation functions are the exact solutions of the field equations in the frequency domain.

(d) The possibility of immediate extension to three-dimensional problems.

(e) The possibility of computational savings by interpolation between eigenfrequencies.

It is also possible to add directly to the global impedance matrix the effect of concentrated masses. For the case of springs and dashpots acting between structural nodes we decided to duplicate the numbering and to distinguish between initial and final nodes, as well as to relate the direction of the spring–dashpot system to one bar of the structure.

Once the global impedance matrix $K(w)$ has been assembled, the load matrix (one column for every load case) $F(w)$ can be organized for every frequency

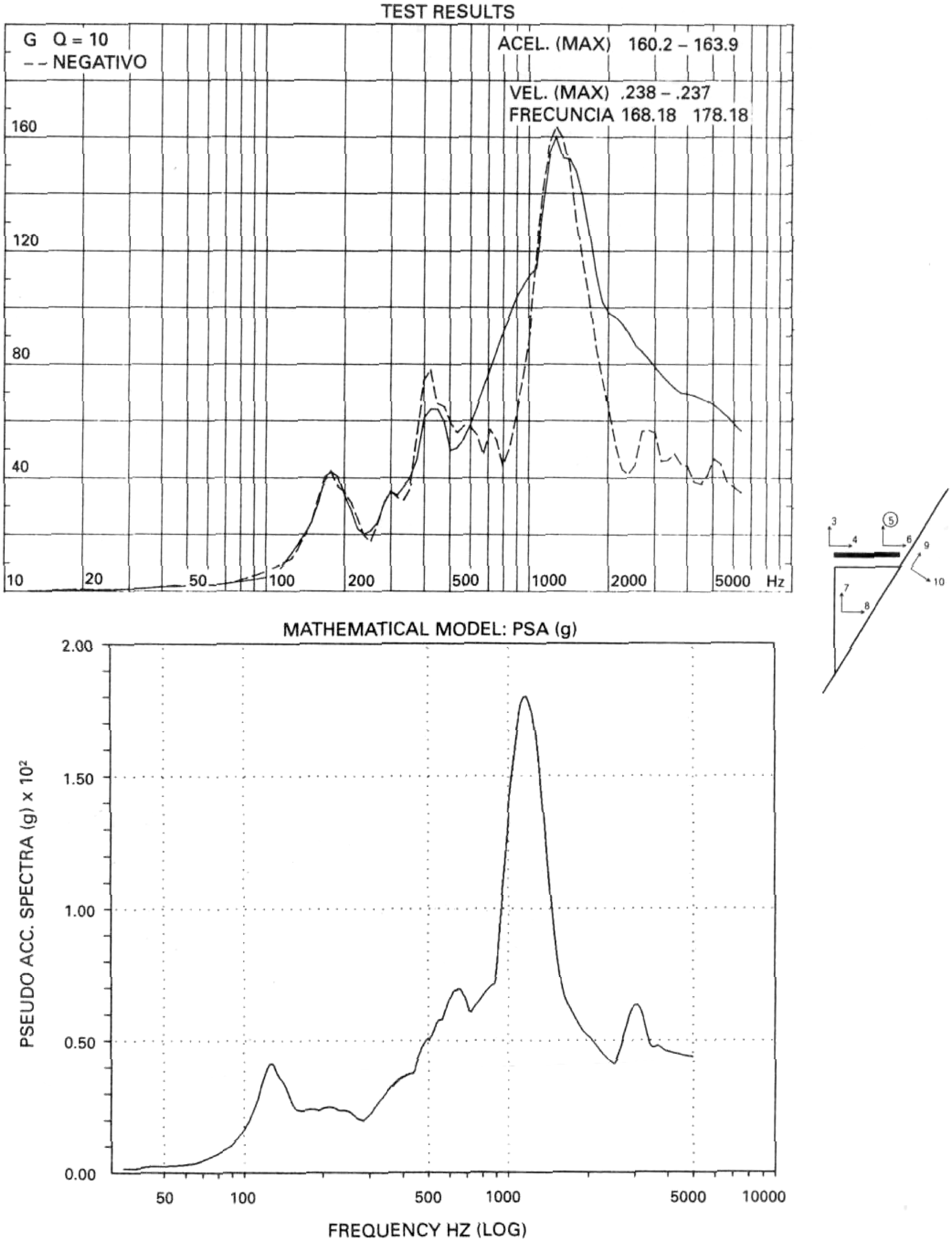

Fig. 5. Test and theoretical results.

and the displacement fields $x(w)$ are obtained by solving

$$x(w) = K(w) \cdot F(w)$$

$$\dot{x}(w) = i \cdot w \cdot x(w)$$

$$\ddot{x}(w) = -w^2 \cdot x(w).$$

An inverse Fourier transformation block, similar to that used in program ONDA-F, then produces the superposition of the different frequency responses, to synthesize the time responses of interest.

To allow the treatment of load cases with different frequency contents the first part of the process is done using unit load cases for every frequency; then a multiplication by the load frequency component is conducted and, finally, the inverse transformation to the time domain is executed. A simplified scheme of the whole process is summarized in Fig. 3.

4. PARAMETRIC STUDIES

As has been explained, the parametric studies for the undamped and the damped cases have been organized in three steps or families: in the first one, that contains 21 runs, the basic model (A) of Fig. 2 has been tested. The idea was to try to adjust orders of magnitude, to analyze the frequency contents, to analyze the influence of the spring stiffnesses and damping values, and to see the type of damping to be imposed, i.e. viscous, hysteretic, etc. Finally, it seems that a damping ratio on the order of 1–2% for the structure and about 40% in the damping plaster layers produces reasonable results. It was also necessary to play with the stiffness of the hanging strips in order to adjust the evolution of some peaks in the acceleration response spectra.

For the second model of the equipment plate (model B of Fig. 2), a total of seven undamped and five damped ones were run in an effort to fit the horizontal behavior of the plate. In spite of these and other extreme situations that were tried and disregarded after their analysis on the screen, it was clear that the hypothesis of a rigid connection between the mass and the plate was unable to explain the high horizontal accelerations that were registered. The tests were repeated, changing the data acquisition chain to see if there were some calibration errors, but the results were similar. An analysis of the computed model deformation showed that the results are consistent, i.e. the structure reacts against the large mass, which reduces the level of the horizontal acceleration.

A further look at the physical model showed that the fixation of the mass to the rigid plate was done through bolts embedded in a plastic poting, the stiffness and shape of which are randomly dependent on that of the perforated hole. Therefore it was decided to adjust the model by detaching the mass and the plate while maintaining one elastic connection whose value was fixed according to a frequency of about 200 Hz that was persistently absent in the parametric study. With this model (model C of Fig. 2) we immediately obtained the level of horizontal acceleration although some of the frequency spectra were distorted. It has been necessary to run five undamped cases with this philosophy and four damped cases in order to obtain acceptable results.

Figures 4 and 5 present results (test and theoretical) at two different points of the structure.

The spectra also seem to reflect the main phenomena, although there are displacements of the frequencies and certain inaccuracies that reflect the difficulty of the problem and the high sensitivity of the system to small variations of the material properties.

5. CONCLUSIONS

The main conclusions that can be drawn after the extensive computational effort that has been developed are as follows.

(a) Prediction of this kind of phenomenon is a really difficult task. About 50 runs have been necessary to obtain a satisfactory fitting.
(b) The computational system used to analyze the problem is very effective.
(c) The level of accuracy that can be reached possesses a precision that is good enough from an engineering viewpoint, although, certainly, from a scientific viewpoint it could be improved.
(d) The sensitivity of the model to small details is large, but a careful modeling of the structure produces almost immediately the orders of magnitude of the acceleration.

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